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An Investigation of Nonuniform Dose Deposition from an Electron Beam

by William Lilley and Kieu X. Luu

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William Lilley and Kieu X. Luu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Attn: AMSRL-WT-NG
2800 Powder Mill Road
Adelphi, MD 20783-1197

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In a search for an explanation of nonuniform electron-beam dose deposition, the Integrated TIGER Series (ITS) of coupled electron/photon Monte Carlo transport codes was used to calculate energy deposition in the package materials of an application-specific integrated circuit (ASIC) while the thicknesses of some of the materials were varied. The thicknesses of three materials that were in the path of an electron-beam pulse were varied independently so that analysis could determine how the radiation dose measurements using thermoluminescent dosimeters (TLD’s) would be affected. The three materials were chosen because they could vary during insertion of the die into the package or during the process of taking dose measurements. The materials were aluminum, HIPEC (a plastic), and silver epoxy. The calculations showed that with very small variations in thickness, the silver epoxy had a large effect on the dose uniformity over the area of the die.

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1. Introduction

This report examines a possible cause of nonuniform dose measurement data obtained in a dose-rate evaluation of an application-specific integrated circuit (ASIC). The ASIC was evaluated in a transient radiation environment produced by a pulsed electron beam generated by the FX-45 Van de Graaff pulse generator at the Army Research Laboratory (ARL) high-intensity flash x-ray (HIFX) facility. An array of thermoluminescent dosimeters (TLD’s) was used to measure the dose on the top side of an ASIC package after electrons passed through the die from the bottom side of the package (see fig. 1). During an ASIC evaluation, dose measurements across the array of TLD’s varied and indicated a nonuniform pattern over the area of the die after one radiation pulse from the FX-45 pulse generator. It was also noted that after three successive shots, the nonuniform pattern measured by the TLD’s remained the same. This nonuniform pattern over the area of the die could be caused by (1) the electron beam drifting from the center line as it passes through the evacuated drift tube or (2) an inconsistency of material thickness between the TLD’s and the electron beam. This report examines the hypothesis that the layers of materials between the TLD’s and the electron-beam source varied in thickness.

TLD’s provide an indirect method of measuring the ionizing radiation dose to a packaged silicon die. Because of their placement (see fig. 2), the TLD’s absorb radiation energy after it passes through the materials in the path of a pulsed electron beam. We calculate the energy deposited in the silicon die by multiplying the dose measured by the TLD’s with a calculated correction factor.

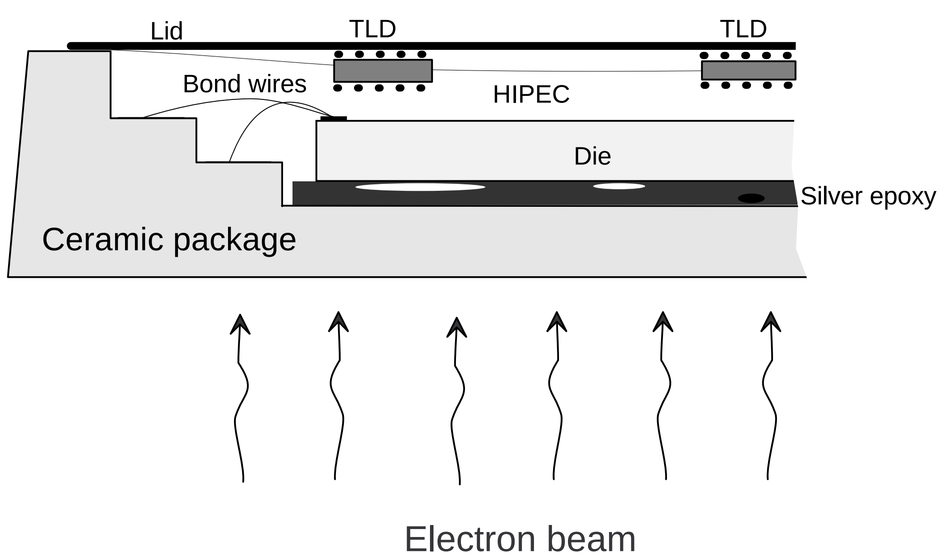
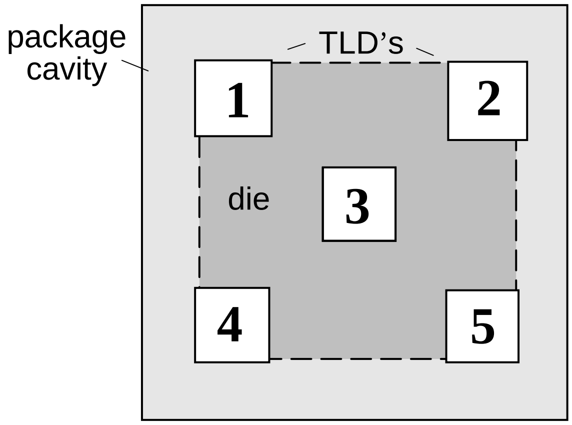


Figure 1. Side view of packaged die with respect to electron-beam pulse.

Figure 2. Arrangement of TLD's in package cavity.



The correction factor was calculated with the TIGER program, a coupled electron / photon Monte Carlo transport code.[1] We used the TIGER code to help evaluate our hypothesis for these nonuniform TLD readings. The TIGER code calculated the data using the material type, density, and thickness parameters that make up the leaded chip carrier (LCC) package and the packaging materials.

We began by incrementally varying the thicknesses of the packaging materials, because they could vary during the die-package assembly process. These material thicknesses were varied in realistic amounts so that we could see if they could in fact cause the observed nonuniformity in the measured radiation dose across the area of the die.

[1]*Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Code System (Version ITS 2.1), Sandia National Laboratories, Radiation Shielding Information Center, updated 2 March 1988.*

2. Radiation Source and Measurements

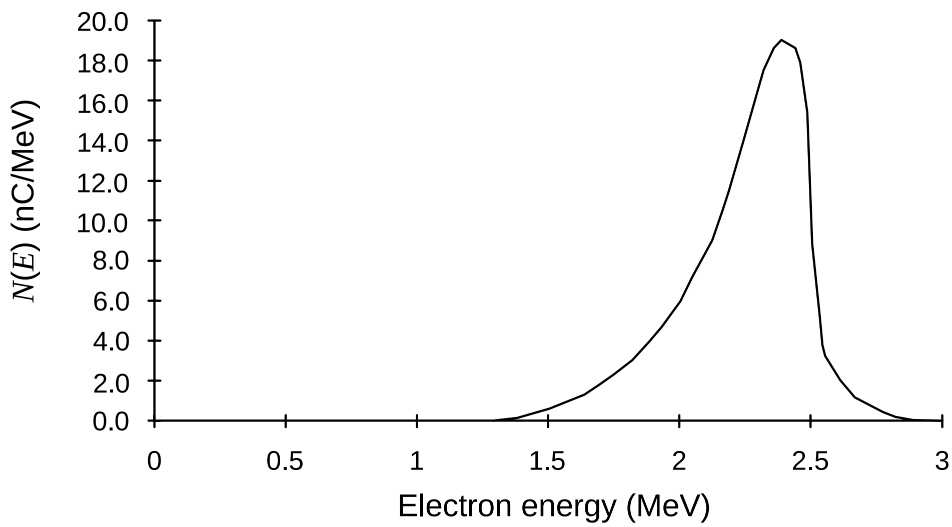
2.1 High-Intensity Flash X-ray (HIFX) Facility

The HIFX facility has an Ion Physics Inc. pulsed Van de Graaff generator (model FX-45) that was used for the electron-beam source. The FX-45 machine produces a 20-ns pulse (full width, half maximum—FWHM), with a maximum energy of approximately 2.9 MeV. Figure 3 shows a graph of the FX-45 electron energy spectrum. The hardware in the evaluation setup was arranged for a maximum output, through the evacuated drift tube, of 1.0×10^{12} rads(Si)/s. The hardware setup used for the test is shown in figure 4. The FX-45's electron-beam output was controlled by the use of apertures in the evacuated drift tube. The use of these apertures was documented in a previous experiment relating to HIFX electron-beam dosimetry.[2] The hardware required for this setup was a 60-cm evacuated drift tube and an aperture of 0.359 in.

2.2 TLD's

TLD's are commonly used in radiation hardness testing because they are small (typical size is a chip of $3.2 \times 3.2 \times 0.9$ mm), inexpensive, and easy to use, and they can retain dose information for a relatively long period of time after exposure to radiation. The TLD's used in this experiment were manganese-activated calcium fluoride (CaF_2:Mn). The minute concentration of manganese impurity serves

Figure 3. FX-45 electron energy spectrum.



[2]*Gregory K. Ovrebo, Steven M. Blomquist, and Steven R. Murrill, A HIFX Electron-Beam Dosimetry System, Army Research Laboratory, ARL-TR-363 (February 1994).*

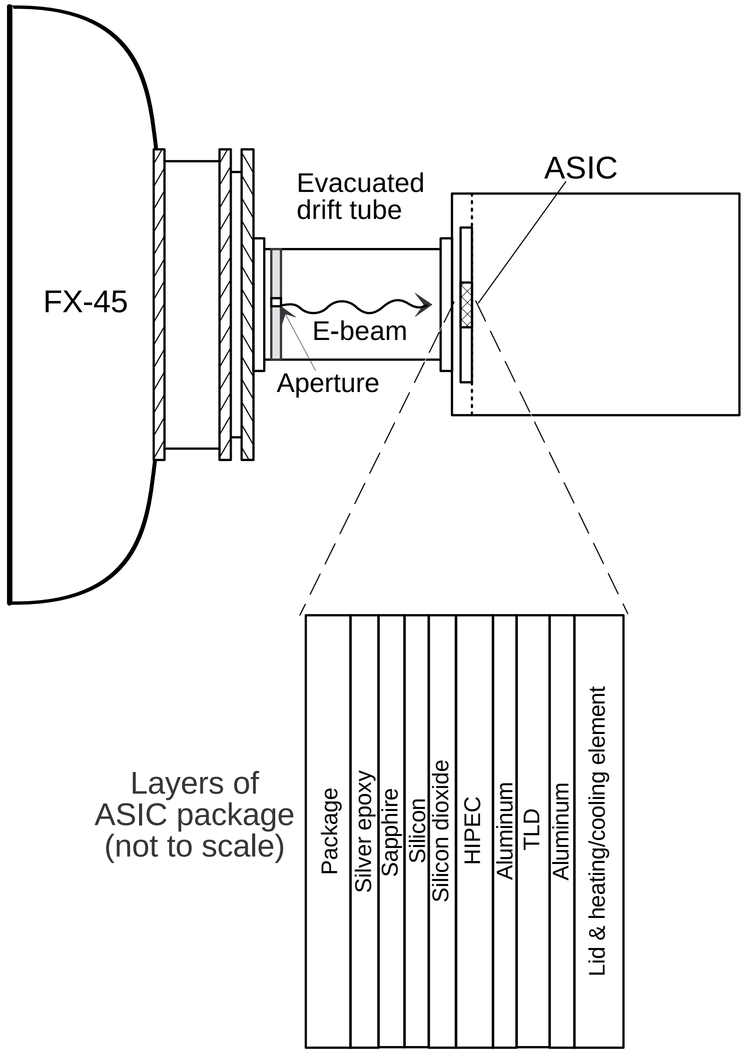


Figure 4. Configuration of electron-beam hardware setup.

as an activator that traps secondary electrons produced by the ionizing radiation. When the TLD material is heated, the trapped electrons are released and return to a lower energy state. The excess energy from the electron returning to a lower energy state is released as visible light. This thermoluminescent emission is viewed by a photomultiplier tube as an integrated light output that is proportional to the energy absorbed by the TLD's. If we take into account the absorption of electron energy (using the TIGER program), we can relate the radiation dose absorbed by a layer in the chip package to the radiation energy received by TLD's. The dose absorbed by the silicon layer of the die where the integrated circuit is patterned is of particular interest.

During an electron-beam irradiation, an array of five TLD's was placed in the IC package a few millimeters apart from each other. With this TLD arrangement, one would expect the radiation energy

received by the TLD’s to be uniform and symmetric over the area of the array (in this case the area around the die). However, in three different shots, the actual TLD readings taken during the evaluation varied from 1.5 to 6.1 krads(Si) (see table 1). We suspected that there might be nonuniform attenuation from the package materials and, to investigate our hypothesis, made TIGER calculations with varying thicknesses of the three materials. We then compared the results from each of the material thickness calculations to one another to observe whether varying the material thicknesses had any significant effect.

Table 1. TLD data from dose-rate evaluation.

Test shot	TDL readings (krads(Si))				
	1	2	3	4	5
1	5.63	2.10	5.71	0.72	2.50
2	6.06	3.90	5.35	0.56	2.08
3	6.11	4.04	5.68	1.53	2.96
Average	5.93	3.35	5.58	0.94	2.51

3. The Integrated TIGER Series (ITS) of Coupled Electron/Photon Monte Carlo Transport Codes

According to the documentation of ITS, the software package "permits a state-of-the-art Monte Carlo solution of linear time-integrated coupled electron / photon radiation transport problems with or without the presence of macroscopic electric and magnetic fields of arbitrary spatial dependence." This means that TIGER is a powerful and versatile software package that allows the user to tailor the coding of the program, using a parameter setup list, to meet specific application needs. The basis of TIGER is the Monte Carlo code, which is a computer simulation technique that models real physical systems by using random numbers to simulate the statistical fluctuations and probabilities that a certain event might occur within a complex system. For this project, the ITS was programmed to track the energy state of an electron as it passed through the layers of different package materials of varying thicknesses and densities before bombarding the die and TLD's (table 2 is the material parameter list). The program tracked 100,000 electrons to construct a working model of how energy is deposited at each layer of the chip under our experimental conditions. Applying statistical physics and probability principles, the program generates data compiled from the run. In this case, the data of importance are the energy deposition in the TLD's and in each of the layers where the thickness parameter was varied.

Each run of ITS on the VAX computer mainframe takes an average of three to five hours, as the large volume of numerical data is generated, manipulated, and analyzed. Despite the time taken up in each simulation run, it is very cost effective and practical. The alternative is to repeat the experiment at the HIFX facility to verify the TLD data; the average cost of testing at HIFX is $3000 per day.

Table 2. TIGER dosimetry material specification and nominal thicknesses.

Layer				Thickness
Structure	No.	Material	TIGER material definition	(cm)
Package	1	Ceramic	Al 0.529 O 0.471 density 3.69	0.0762
	2	Tungsten	W	0.00254
	3	Nickel	Ni	0.000254
	4	Gold	Au	0.0001524
Silver epoxy	5	Silver	Ag	0.002388
Die	6	Sapphire	Al 0.529 O 0.471 density 3.96	0.0508
	7	Silicon	Si	0.0005
	8	Silicon dioxide	Si 0.47 O 0.53 density 2.3	0.0002
HIPEC	9	HIPEC	C 0.58 N 0.12 O 0.28 H 0.02 density 1.0	0.01
TLD, capsule	10	Aluminum	Al	0.00254
	11	Calcium fluoride	Ca 0.51 F 0.49 density 3.18	0.0889
	12	Aluminum	Al	0.00254
Lid, heating /	13	Kovar	Ni 0.29 Co 0.17 Fe 0.54 density 8.34	0.0381
cooling finger	14	Aluminum	Al	1.0

4. Parameters Varied

The layers of the materials that were varied in the TIGER parameter setup list were the aluminum foil layers, the silver epoxy layer, and the HIPEC layer. The aluminum foil serves as a holding capsule surrounding the TLD. The silver epoxy is an adhesive that attaches the die into the cavity of the package. The HIPEC is a rubbery hydrocarbon sealant between the die and the package lid that minimizes internal electromagnetic pulse and air ionization. These layers were chosen because of possible variability in their thicknesses during the assembly process. In contrast, the LCC package itself was manufactured with tight tolerances, and a high degree of consistency can be assured.

The aluminum layers were varied in increments according to the possible number of aluminum layers that may encapsulate a TLD. Since the aluminum foil was of a constant thickness (0.00254 cm), the actual thickness itself could not be varied. However, the number of times a TLD was wrapped by the aluminum could be varied. The nominal parameter for the aluminum capsule around the TLD was one layer in front and one layer in back. Since layers of the encapsulation may overlap, there could be two layers of aluminum in front and one in back of the TLD, or vice versa. Combinations of two and three layers around the TLD were unlikely to happen; however, to see the contrast in a larger amount of data, we performed the calculations for that combination also. The different combinations in which the aluminum layers around the TLD were varied are shown in table 3.

We originally planned to increase the silver epoxy and HIPEC thicknesses by only 5 to 10 percent to see if a very small change in thickness would significantly affect the TLD reading. However, TIGER calculations showed that these changes in material thicknesses did

Table 3. Variations made in layers of aluminum encapsulation around TLD.

	Aluminum encapsulation			
	Front		Back	
Trial No.	No. layers	Thickness (cm)	No. layers	Thickness (cm)
*1	1	0.00254	1	0.00254
2	1	0.00254	2	0.00508
3	2	0.00508	1	0.00254
4	2	0.00508	2	0.00508
5	2	0.00508	3	0.00762
6	3	0.00762	2	0.00508
7	3	0.00762	3	0.00762

**Nominal values*

not have a significant effect on the dose deposition in the TLD. We then decided that increments in thickness that were proportional to the layer variations during the assembly process would be more reasonable and practical. For example, in the case of the silver epoxy layer, the nominal value for the thickness used in the TIGER calculation was 0.002388 cm (or 0.94×10^{-3} in.). From this point we decreased the thickness by approximately 10 percent to 0.0021492 cm (or 0.846×10^{-3} in.) and then incrementally increased the thickness value by approximately 10 times to 0.02286 cm (or 9.0×10^{-3} in.). These thicknesses corresponded to the range of values for the silver epoxy that could occur from the application during the assembly process. This information was obtained from a discussion with Katherine Phillips of Harris Corporation, who assembled the IC packages.* The same approach was used for the thickness of the HIPEC, but the values were larger since the volume for the HIPEC filler was greater. Table 4 shows the actual thickness values used in the TIGER code calculations for the silver epoxy and HIPEC layers. When the thickness for the silver epoxy was varied, the HIPEC thickness was set to its nominal value (0.1 cm). The same was true when the thickness of the HIPEC was varied; the silver epoxy thickness was set to its nominal value (0.002388 cm).

Table 4. Variations made to silver epoxy and HIPEC thicknesses.

Trial No.	Silver epoxy[a] thickness (cm)	Trial No.	HIPEC[b] thickness (cm)
8	0.0021492	15	0.0750
9	0.0024994	16	0.0900
10	0.0038100	17	0.0095
11	0.0050800	18	0.1050
12	0.0152400	19	0.1250
13	0.0203200	20	0.1500
14	0.0228600	21	0.2000

[a]*Nominal value = 0.002388 cm*
[b]*Nominal value = 0.1 cm*

Phone conversation with Katherine Phillips, Harris Corporation Semiconductor Division, related to variations in silver epoxy thickness (July 1993).

5. Results

The data generated from the TIGER calculations showed that there was no significant change in the energy deposition in the TLD or the die when the layers of the aluminum encapsulation were varied from a reasonable minimum thickness to a reasonable maximum thickness. The energy deposition in the TLD and the die remained relatively unchanged as one, two, and three layers of aluminum foil were alternatively specified for the TLD encapsulation front and back layer.

Figure 5 is a graph of the calculated results from the TIGER code showing very little energy deposition change in the TLD and die while the aluminum layers were varied.

Figure 6 shows that changes made to the HIPEC thickness yielded slight changes in the energy deposition on the TLD. Increasing the HIPEC layer by a factor of approximately 10 resulted in a factor of 2.08 decrease in the energy deposition on the TLD for the overall thickness range of calculations. However, the actual thickness of the HIPEC can vary only within the difference of the void remaining in the package cavity after the silver epoxy and die are inserted. These values can range from approximately 0.0381 cm up to approximately 0.1 cm (assuming the void is completely filled between the die and the package lid). The energy deposition changed only by a factor of 1.38 over the actual range of HIPEC thickness variations.

Figure 7 shows that thickness variations of the silver epoxy layer yielded a significant change in the energy deposition in the TLD and the die. When the thickness of the silver epoxy was increased from 0.002388 to 0.02286 cm (or 0.85×10^{-3} to 9.0×10^{-3} in.) in the TIGER calculations, the resultant data showed an energy deposition decrease in the TLD of a factor of 4.0 and an energy deposition decrease in the die of a factor of 2.6. The factor of 4.0 decrease in the energy deposition of the TLD is on the order of the measured values shown in table 1.

Figure 5. Calculated energy deposition for various aluminum layers.

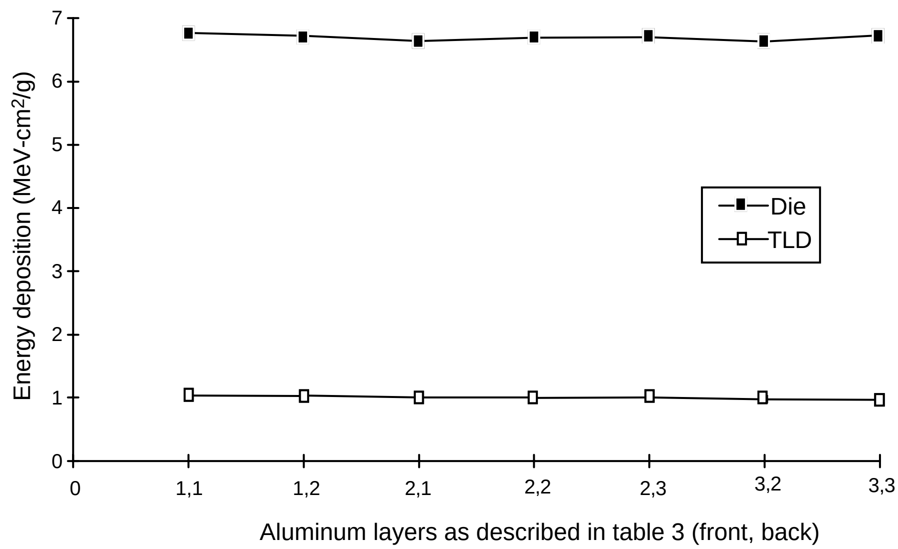


Figure 6. Calculated energy deposition for various HIPEC thicknesses.

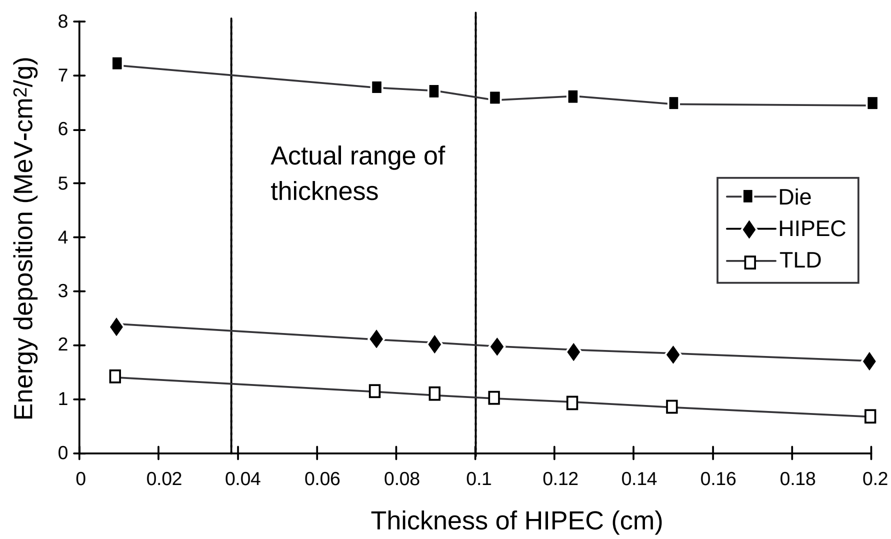
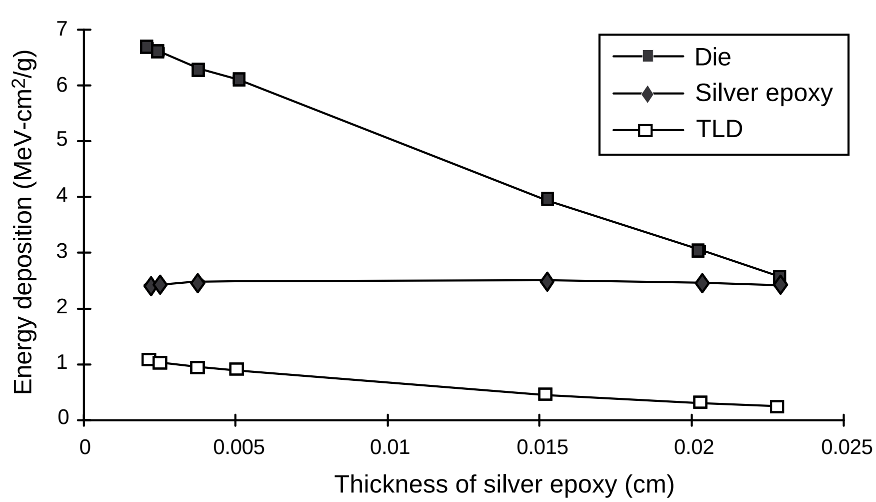


Figure 7. Calculated energy deposition for various silver epoxy thicknesses.



6. Conclusion

The calculations showed that any reasonable variation in the number of layers that make up the aluminum encapsulation of the TLD was not a contributor to the nonuniform TLD readings. Varying the number of layers of aluminum foil that encapsulate the TLD from one to three had no significant effect on the energy deposition in the TLD itself.

The calculations using the variations in the HIPEC thickness also showed an insignificant effect on the uniformity of the TLD readings.

The calculations with realistic variations in the silver epoxy thickness showed that an uneven distribution of the silver epoxy layer underneath the die could account for the nonuniformity in TLD readings. This suggests that if the silver epoxy is applied unevenly with an applicator, the thickness of silver epoxy under the area of the die may be rippled and create voids or bubbles between the die and the package. When the thickness was varied between 0.002238 to 0.02286 cm (or 1.0×10^{-3} to 9.0×10^{-3} in.), the TLD readings could vary up to a factor of four. In a dose-rate evaluation of a particular ASIC, the TLD readings did show up to a factor of six difference (see table 1).[3] Therefore, this difference is very likely the result of an uneven distribution of the silver epoxy.

We cannot be certain that this conclusion is correct since we did not have actual cross-sectional measurements of the material thicknesses. However, from these calculations it seems very likely that the variation in the thickness of the silver epoxy is the primary contributor to nonuniform TLD readings over the area of the die. This also indicates that the die was receiving nonuniform irradiation over its area, and electron-beam dosimetry could be misleading for such situations.

[3] *W. Lilley and W. Gay, Microcircuit Technology Radiation Hardness Assessment: Ionizing Dose-Rate Evaluation of USASSDC AHAT Serial Network Interface, Army Research Laboratory, ARL-MR-117 (March 1994).*

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